Available online at www.sciencedirect.com
ScienceDirect
Renewable and Sustainable Energy Reviews
12 (2008) 1162–1175

RENEWABLE
& SUSTAINABLE
ENERGY REVIEWS

www.elsevier.com/locate/rser

Solar photovoltaic water pumping—opportunities and challenges

Kala Meah*, Sadrul Ula, Steven Barrett

Electrical and Computer Engineering Department, University of Wyoming, Deparment 3295, 1000 E. University Avenue, Laramie, WY 82071, USA

Received 25 August 2006; accepted 13 October 2006

Abstract

Solar photovoltaic water pumping (SPVWP) is a cost-effective application in remote locations in developed countries. The economy and reliability of solar electric power made it an excellent choice for remote water pumping. Ranchers in the western US, Canada, Mexico, and Australia are the biggest portion of the SPVWP system users. Water sources are spread out in the ranchland and power lines are not readily available and refueling and maintenance of stand alone generators is not cost effective. But in the developing countries, where drinking water is number one priority for most of the population the SPVWP has not achieved a great success yet. Even though, the SPVWP has significant advantages a lot of challenges are associated with the SPVWP, especially in operation and maintenance. This paper discusses some policies to make the SPVWP system an appropriate technology for the respective application region.

Keywords: Solar photovoltaic; Water pumping; Appropriate technology

Contents

*Corresponding author. Tel.: +1 307 766 2702; fax: +1 307 766 4689.
E-mail address: kmsujon@uwyo.edu (K. Meah).

1364-0321/$ - see front matter
doi:10.1016/j.rser.2006.10.020

1. Introduction

The solar photovoltaic water pumping (SPVWP) system has its own perspective depending on users. Socio-economic structure varies from country-to-country, even region-to-region in the same country. Thus a solution that is appropriate in one region may be unsuitable in another, either because it is too complex or insufficiently advanced. The same technology might have different applications. For example, the SPVWP applications in the North America, Australia, and Europe are mainly for livestock, wildlife, and vacation homes, but in developing countries the applications are mainly limited to life critical drinking water and micro-irrigation applications.

The main purposes of solar photovoltaic (SPV) are to serve off grid clients and to help protect the environment from fossil fuel's pollution. The USA and other developed countries promote SPV and renewable energy sources to reduce environmental pollution. On the other hand, in developing countries such as in Asia, Africa, and South America the SPV is the only source of electric energy in many villages and remote locations. Pure drinking water is a critical need in these developing countries. Everyday 5000 young children die due to water spreading diseases; mainly diarrhea, which is easily preventable. Furthermore, 1.1 billion people do not have access to drinkable water [1]. A small SPV system could help them to access pure drinking water and improve their standard of life. In developing countries, more than half of the population is below the poverty limit and the cost of a SPV system is beyond their economic resources. This is why the SPV applications are mostly concentrated in the developed countries, such as Europe, America, Japan, and Australia. Fig. 1 shows the SPV module price and production rates from 1975 to 2005, and SPV worldwide installation through 2005 [2–4]. From Fig. 1, it can be seen that, the solar module price has been almost unchanged for the past 20 years, but production rates increased significantly during the last 5 years. Europe, Japan, and USA are the bulk users with a 90% collective share. Only 10% of the SPV systems are installed out of this zone. Australia is a significant SPV system user in the rest of world category. It accounts for 30% of the rest of world usage. If Korea, China, and some Middle Eastern countries like Saudi Arabia and UAE are excluded, then the developing countries are using less than 5% of the world's total available SPV systems. This is simply

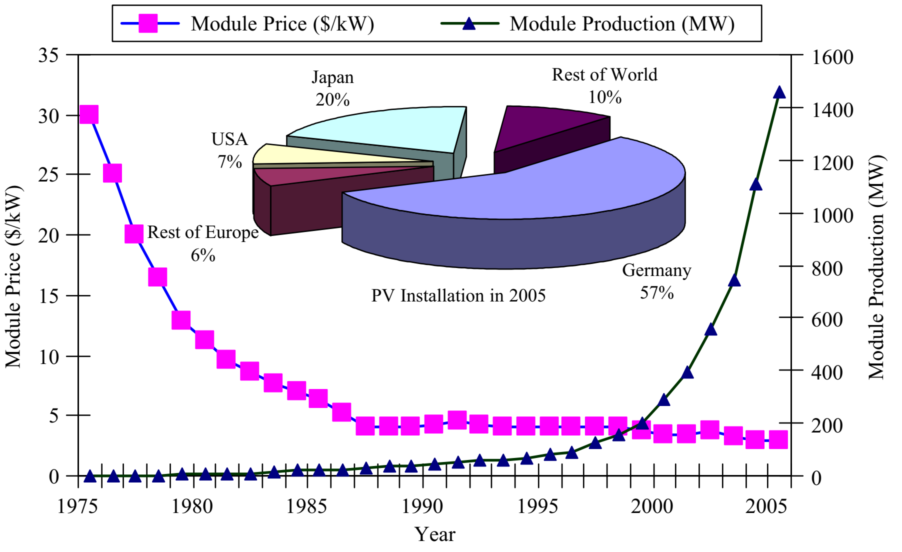


Fig. 1. Module price, production, and PV installation.

because of the cost of the SPV systems and promotion of green power to protect the environment by developed countries.

However, the capital cost is not the only constraint for the widespread use of SPV applications some other challenges are associated with it. Almost all challenges, except capital cost are shared by the developed and developing countries, but the criticality of the challenge may be different. Some of these challenges are listed below:

- Technical:
  - cell efficiency, capital cost,
  - availability of spare parts,
  - skilled technicians for maintenance,
  - adoption of locally available products,
  - operation and maintenance costs.
- Socio-environmental:
  - health,
  - ownership,
  - theft/vandalism,
  - community,
  - demonstration/Educational.

Some of these challenges could be resolved within a short period of time. Others may need a longer time to solve because they are technology dependent.

2. Technology and application

The SPVWP is directly involved with the local community, where grid power is not available. Remote areas are separated from urban facilities. If any technology is

considered for remote application, it should be redesigned according to the socio-economic structure of the particular area. Schumacher is quoted by Dunn [5] as saying, *a project that does not fit, educationally and organizationally, into the environment, will be an economic failure and a cause of disruption*. If a technology is well accepted in developed countries, it might not have the potential in developing countries. Technology should have appropriate adaptation characteristics to fit in the environment. Dunn [5] describes some of these principles and criteria for the appropriate technology.

The principle aims of development are

I. to improve the quality of life of the people,
II. to maximize the use of renewable resources,
III. to create work places where people now live.

The solutions chosen should satisfy the following criteria:

a. employ local skills,
b. employ local material resources,
c. employ local financial resources,
d. be compatible with local culture and practices,
e. satisfy local wishes and needs.

The basic requirements of a community are food, water, clothing, shelter, health care, hygiene, sanitation, education, and training. All of these requirements are directly related to pure water. The SPVWP system could assure an uninterrupted pure water supply by satisfying the five criteria above. The developed and developing countries have their own perspective to satisfy the local requirements, which will be discussed later. Before that the SPVWP system, its applications, and reliability assessment should be discussed.

3. Solar photovoltaic water pumping system

The photovoltaic (PV) system is based on semiconductor technology that converts sunlight into electricity. This is a proven technology but costs more than other electricity generation methods such as a power plant based on coal, oil, natural gas and conventional hydro electric conversion techniques. Fig. 2 shows a schematic diagram of a solar water pumping system. This section provides a brief discussion of the main components of a SPVWP system designed for well water access for people, and livestock and wildlife in remote locations.

3.1. The PV array

The source of electrical energy of the SPVWP systems is the PV arrays. Every PV array has its own (I–V) characteristics. The maximum power point (MPP) of the PV array depends on several factors including onsite solar radiation, temperature, the connected load, and if the load is directly connected. For a specific power output, array size depends on the efficiency of the cell. Solar cells are divided into three

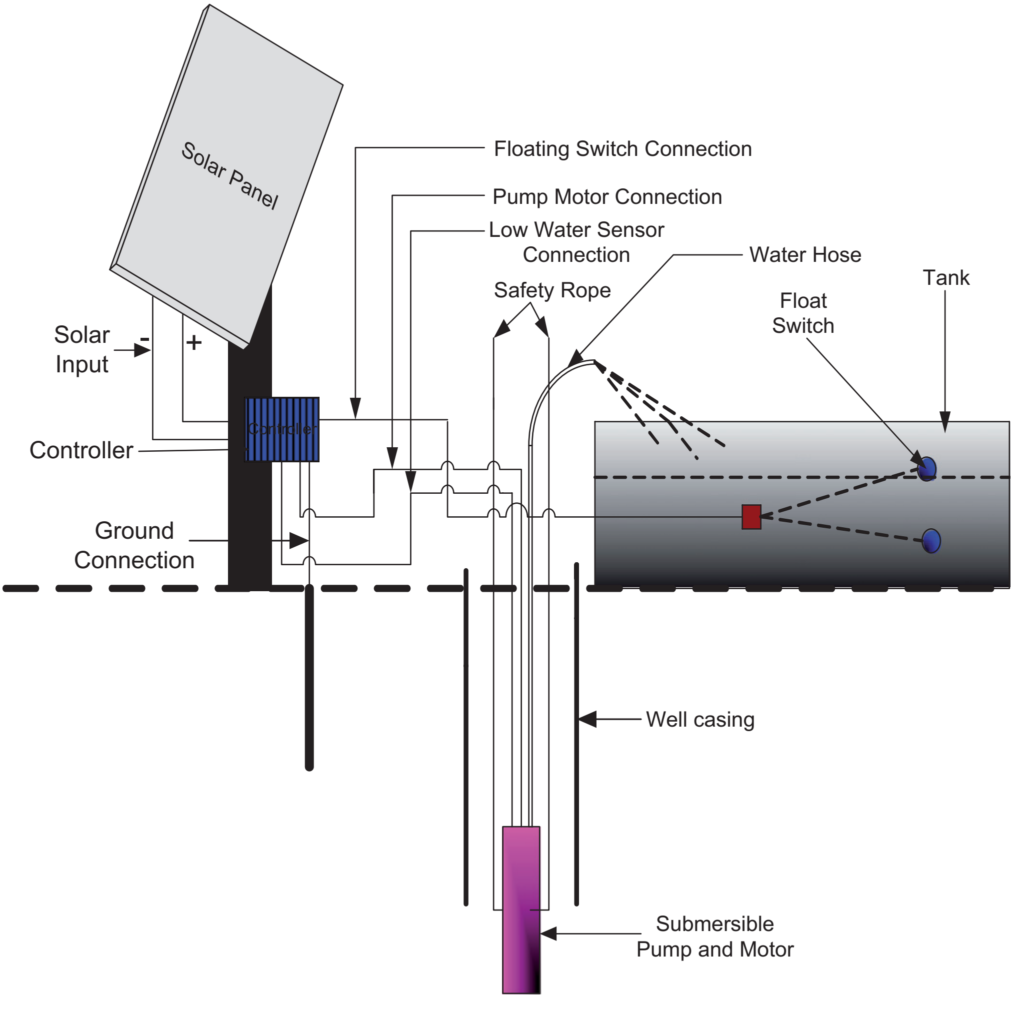


Fig. 2. Schematic diagram of a solar water pumping system.

categories according to the type of crystal material used in fabrication: mono-crystalline, polycrystalline and amorphous. The level of efficiencies currently available is about 7%, 15%, and 17% for amorphous, polycrystalline, and monocrystalline silicon, respectively.

3.2. The pump

Solar water pumps may be subdivided into three types according to their applications: submersible, surface, and floating water pumps. A submersible pump draws water from deep wells, a surface pump draws water from shallow wells, springs, ponds, rivers or tanks, and a floating water pump draws water from reservoirs with

adjusting height ability. There are also several types of pumps according to their pumping principle:

- centrifugal pumps, where liquid is sucked by the centrifugal force created by the impeller and the casing directs the liquid to the outlet as the impeller rotates. The liquid leaves with a higher velocity and pressure than it had when it entered the pump,
- screw pumps, where a screw traps the liquid in the suction side of the pump casing and forces it to the outlet,
- piston pumps, where motion of the piston draws water into a chamber using an inlet valve, and expels it to the outlet using the outlet valve.

The selection of an appropriate pump in a solar water pumping application is solely site dependent, such as water requirement, water height, and water quality.

3.3. The pump motor

Several types of motors are currently available in the market, such as AC, DC, permanent magnet, brushed, brushless, synchronous and asynchronous, variable reluctance, and many more. The PV array could be directly connected to the motor, if the application needs a DC motor. If the application needs an AC motor, an inverter (usually called a controller) needs to be placed in between the PV array and the motor. The motor and pump are built in together for the submersible and floating systems. In this case, the consumer does not have an option to choose them separately. In the surface system, it is possible to choose the pump and motor separately and evaluate their performance along with the controller and panel.

3.4. The controller

The controller is needed if the AC motor is in use. The controller effectively isolates the PV array from the pump motor system for greater safety and provides the pump motor with the optimum voltage/current for the site conditions. The controller also protects the pump motor from running dry and conserves water by turning off the system when the tank is full. However, one of the most vulnerable components in the SPVWP system is the controller because it contains sophisticated electronics and has to operate in various and often harsh environmental conditions.

4. Performance evaluations

The SPVWP system has been used for almost three decades. The economic analysis for SPVWP may be divided into two categories: developed countries and developing countries. The SPVWP has proven financially suitable for remote locations in the developed countries [6]. Local level operation and maintenance (O and M) could be used to improve the life cycle and to reduce the O and M costs. But in developing countries, the cost of the SPV system is not affordable for the most of the people in rural areas. At present, the SPVWP system is not a suitable alternative to conventional energy systems or diesel generators in developing countries [7–9]. To make the SPVWP system cost effective in developing countries, government subsidies are suggested by Purohit [7], which is not an

ideal long term solution. In developing countries, the hand pump is used to supply drinking water, which is shown in Fig. 3 along with the SPV water pump. The hand water pump could be useful for a small village to supply drinking water, but for irrigation purposes it requires constant physical labor, which makes it unsuitable. During the dry season, the water level goes down and the hand pump can barely supply drinking water



Fig. 3. The hand water pump and SPV water pump (Bangladesh and India).



Fig. 4. The SPVWP system in a ranch, Wyoming, USA.

needs. On the other hand, the SPV powered water pump operates autonomously and supplies water as long as the sun shines. It could be possible to make the SPVWP system economically competitive with a stand alone diesel generator by following the five steps described in [5], which will be discussed in detail later. In contrast, in developed countries, the main application of the SPVWP is for the livestock and wildlife watering in remote locations. Fig. 4 shows the SPVWP application at a Wyoming ranch. The performance evaluation is a real time judgment for any technology and better care could be taken by learning from the previous mistakes. The next section will present the reliability assessment of the SPVWP system in developed and developing countries.

5. Reliability assessment

The long life cycle of a SPVWP system can be assured by proper maintenance and availability of spare parts in the local market. Some reliability assessment reports for 10 years of operation have been reported in [8,9]. In Thailand a survey was conducted between 1995 and 1998 on 489 SPVWP systems. Out of 489 systems, 220 systems (45%) have failed and were not pumping water any more, 88% of them failed within 7 years. The main types of failure are as follows: broken water taps 30%, motor/pump failures 27%, pipe leakages 18%, and inverter failures 17%. The pipe and pump failures are due to blockage because of water plants and sediments becoming lodged within the system [8].

Espericueta [9] presented a survey on 46 systems in Mexico to evaluate the reliability and user acceptance of SPVWP systems after owning them for as much as 10 years. Out of 46 systems, 18 systems (39.13%) were not operating and 26 component failures were documented. Types of failure modes were as follows: pump/motor failure 54.2%, controller/inverter failure 20.8%, well 16.7%, and dismantled system 8.3%.

The University of Wyoming Motor Testing and Training Center (UWMTTC) supervised the installation of 15 SPVWP systems between 1991 and 2002. The UWMTTC also installed 80 SPVWP systems in 2005–2006. A survey was conducted on systems installed between 1991 and 2002, and information on 11 of these systems is available. One system (9%) out of 11 is not operating because the well dried out. Sixteen failures have been reported: 10 (62.5%) pump/motor failure, 4 (25%) controller failure, 1 (6.25%) pipe leakage, and 1 (6.25%) electric cable failure. The respective owners have fixed them with appropriate spare parts.

By analyzing the failure scenarios above, it can be concluded that most of the SPVWP systems can be restored to service with the simple replacement of the pump/motor, controller, and other components. Technical knowledge and availability of spare components/parts play an important role in the successful O and M of the SPVWP systems. In this respect, the developed countries have greater advantages over the developing countries because of the social, economical, and technical infrastructure already in place.

6. Opportunities, challenges, and solutions

The SPVWP has been in operation around the globe for a long time and is successfully serving people in need, livestock, and wildlife in remote locations [6–14]. Despite the great success of the SPVWP applications, some challenges are still hindering its broader application. The challenges are discussed here and probable solutions based on [5] are also mentioned.

6.1. Capital cost

The SPV array, which is the source of electricity in a SPVWP system costs 50–75% of the total system cost. The PV array cost is directly related to the solar cell efficiency, which is only 24.7% for silicon (crystalline) and 20.3% for silicon (multicrystalline) under standard testing conditions (air mass (AM) 1.5 spectrum, irradiance $1000\,W/m^2$, at $25\,^{\circ}C$) [15]. But the ambient conditions are different and the module efficiency is 3–5% lower than the cell efficiency due to glass reflection, frame shadowing, temperature, etc. The available commercial solar modules typically have efficiency around 15% and rapid improvement in this value is very unlikely. The capital investment of the SPVWP system is not the main challenge in the developed countries, but in the developing countries it is a big challenge because the per capita income is very low compared with the developed countries. The capital cost could be minimized using local skills, local materials, and local financial resources. The installation cost of the SPVWP system is a bulk part of the total cost. If local people are trained to install a system, the overall system cost is reduced significantly. Some materials could be purchased locally, such as support structures, pipes, and electrical accessories. This will help further reduce capital investment. In developing countries, most of the SPVWP systems are government subsidized or donated by nongovernment organizations (NGOs). This is not a recommended practice in the long run because one typically does not care for a system they do not have a financial stake in for it. Sometimes, a committee is formed to take care of the system, where a community or village leader enjoys the ultimate system benefit. As a result, the whole structure collapses. A better approach is to involve everybody in a community/village, which could be done by using local financial resources. The government or NGOs could finance the initial investment because the large amount of money may not be affordable by the community/village people. After that, the system recipients could pay the money back over a 1–5-year period with or without any interest depending on established polices. Every year, the community/village people should elect their own committee to take care of the SPVWP system. In this approach, the recipients feel the responsibility and everybody in the community/village is an owner. Nobody will have more rights than others. Theft/vandalism and ownership issues could be reduced significantly by involving everyone in the community/village with an equal right. To take care of the maintenance and replacement costs, the committee could raise a little money every month according to the ability of the people. The more wealthy people in the village/community could step forward to donate more money to support the system operation.

The concept of recovering the capital cost over the years could be applied in the developed countries as well. The drinking water supply using SPVWP systems is not mandatory in developed countries as it is in developing countries. Most of the SPVWP system, in developed countries are being used in ranches and in vacation homes, and personally owned. This concept will give the system recipient great relief and help to encourage more widespread use of SPVWP based systems.

6.2. Operation and maintenance issues

The lifetime of the SPVWP system is directly dependent on proper operation and regular maintenance. If a system is out of operation, the people and livestock have to go back to an unsafe water supply. Immediate restoration of system operation is critical, which could be done by using local skills and materials. A pool of locally skilled people can be created

through workshops and training. Furthermore, local machine shops could carry the spare parts if locally skilled people are available to use them. This will reduce both O and M costs and system down time, and create local employment opportunities. Locally skilled people are familiar with local culture and practices, and would be able to satisfy local needs and wishes.

6.3. Health

The SPVWP system provides safe water to the community/village, livestock, and wildlife. According to UNICEF, 21% of children in developing countries are living without a safe water source within a 15 min walk of their homes and 1.6 out of 11 million preventable child deaths every year are due to the lack of a quality water supply [16].

However, the water from the SPVWP system could be contaminated if proper care is not taken. The well should be completely covered, the reservoir should be cleaned regularly, the water needs to be protected from any human or animal waste, and the siting must be far away from any sewage source. Overall good fencing would go along way towards protecting the system and the water supply.

6.4. Simplified system design and water conservation

Capital and O and M costs are the vital issues for a SPVWP system, which could be minimized using simplified systems wherever possible. Direct coupling between PV arrays and various DC motors is possible and cost effective [17]. Active solar position tracking could help to capture more sunlight in the morning and late evening, but the wind interrupts the tracking and does not always track the sun [18]. For a simplified system, tracking needs to be avoided to reduce the maintenance cost. In such an installation, maintenance is reduced by at least 25% based on survey reports discussed earlier and the capital cost is also reduced significantly. To provide more flexibility to the SPVWP system and to make it autonomous, a simple controller with low voltage and tank full sensors could be introduced, which is still cheaper and less complicated than an inverter for AC motors. The tank full sensor helps to improve the water conservation in remote locations, where water is needed the most.

6.5. Workshop and training

Local level operation and maintenance (LLOM) is the key to make the SPVWP system cost effective, sustainable, and long lasting. The LLOM could be achieved by educating local people through workshops, demonstrations, and training. A demonstration trailer helps people to understand the basic principle and equipment of the SPVWP system. Fig. 5 shows a demonstration trailer built by the UWMTTC. Practical training could be arranged during installation.

7. Economic analysis

In comparative cost analysis, the simplified SPVWP system with local materials (whatever is useable) and skills is considered. The net profit is considered as the difference between variable costs of a conventional diesel generator and variable costs of a SPVWP



Fig. 5. Demonstration trailer for the solar and wind energy.

Table 1
Cost estimation of SPVWP system

Description	Cost (US$)	
	USA	Bangladesh
PV module	4500	4500
Support structure	200	50
Controller	200	200
Transportation (per year)*	75	15
Motor/pump	750	750
Installation	1000	200
O&M (per year)*	50	10
Accessories	200	100

*Variable cost of SPVWP system.

system. A 1 kW, 50 m pump head SPVWP system is compared with 2 kW, 50 m pump head conventional diesel generator water pumping (CDGWP) system in developed and developing countries. The developed country data are based on the USA and the developing country data are based on Bangladesh. All costs are given in terms of US dollars, US \$1.00 = 69.49 Bangladesh Taka [19]. Tables 1 and 2 show the cost estimation of a SPVWP system and a CDGWP system, respectively. PV module cost is considered as US \$4.5/Wp. Any process involves manual labor, which is very inexpensive in the

Table 2
Cost estimation of CDGWP system

Description	Cost (US$)	
	USA	Bangladesh
Generator	1000	1000
Fuel (per year)*	500	500
Transportation (per year)*	500	100
Motor/pump	750	750
Installation	500	100
O&M (per year)*	200	100
Accessories	200	100

*Variable costs of CDGWP system.

Table 3
Capital cost estimation over 25 years

System	Cost (US$)	
	USA	Bangladesh
SPVWP	8750	7700
Diesel generator	7950	7450

developing countries. Fuel cost and original equipment costs are the same in both the USA and Bangladesh, but local materials costs are cheaper in Bangladesh. Transportation cost in Bangladesh is very low because the people in remote areas use manual vehicles and only 1% increase per year is considered. The diesel generator needs to be checked everyday to turn it on/off and for refueling, but the SPVWP system needs to be checked once a week. The O and M cost is considered constant throughout the project's life time. The motor/pump and controller need to be replaced every 10 years, while the generator needs to be replaced every 5 years. These costs are considered as constant throughout the project's life time. A conservative 10% increase on gas (diesel, petroleum) price is estimated every year. Over the 25 years of the project's lifetime (based on PV module lifetime), the motor/pump and controller need to be replaced twice, and the generator needs to be replaced four times. Table 3 shows the total capital cost over 25 years by adding all replacement costs. It can be seen from Table 3 that the total capital costs of the SPVWP system and the CDGWP system are comparable over the 25 years span of project's lifetime. However, the fuel and O and M cost of the CDGWP system are very high compared to the SPVWP system.

A number of different methods are used to rank projects and to decide whether or not they are feasible. Three of the most commonly used methods are: (i) payback, (ii) net present value (NPV) and (iii) internal rate of return (IRR). NPV is used to validate a project and to rank it against possible alternatives using the NPV value. NPV can be calculated using

$$\mathrm{NPV} = \sum_{t=1}^{n} \frac{R_t}{(1+k)^t} - C, \tag{1}$$

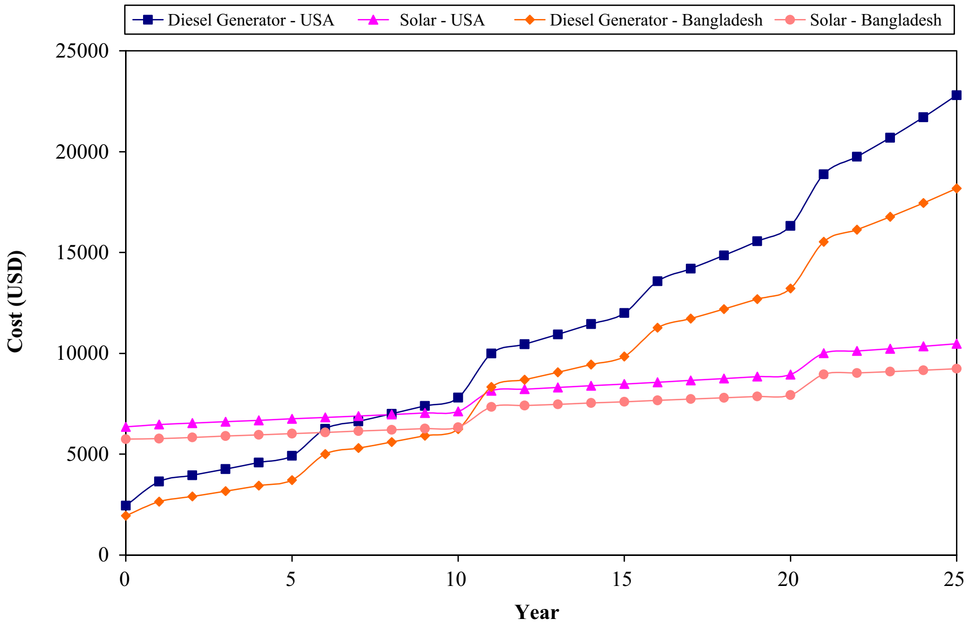


Fig. 6. Total costs comparison year by year.

where R is the net profit, k is the discount rate, n is the project's expected life, which is assumed as 25 years for a SPVWP system and C is the capital cost. For the calculation, R is taken as a constant value, whereas in actual practice it could vary in every year and k is also considered as a constant, which is 7%. The payback time can be calculated from Eq. (1) by setting NPV equals to zero, when k and R are known.

The IRR is defined as that discount rate which equates the present value of a project's expected cash inflow to the value of the project's costs. This also can be calculated from Eq. (1) by setting NPV equal to zero, when n and R are known [20].

The NPVs of the SPVWP system for the USA and Bangladesh are US $3777 and US $166, respectively. The IRR of the SPVWP system for the USA and Bangladesh are 11.47% and 7.24%, respectively. These results indicate that the simplified SPVWP system is economically suitable for both the developed and developing countries with the help of local skills and materials. Even though, the developed countries have more advantages over the developing countries, it is shown that SPVWP is still quite viable. Fig. 6 shows the total cost comparison year by year between the SPVWP system and the CDGWP system in the USA and Bangladesh. Both in the developed and developing countries, the diesel generator water pumping systems have low initial investment. But, the variable costs and replacement costs make the CDGWP system costlier after a few years and in both cases the CDGWP system cost exceed the SPVWP system cost in less than 10 years. The economic analysis shows that the SPVWP system is preferable in the long run.

8. Conclusion

The SPVWP system has proved its aspects technically, economically, and environmentally in developed countries. Some improvements could be done to lower capital

investment costs and to reduce the cost of operational and maintenance services using local level operation and maintenance. In developing countries, capital and maintenance costs are still the main hindrance to the widespread use of SPVWP systems. We have demonstrated that by using local resources such as skills, materials, and finances, the SPVWP system could be economically viable in developing countries and competitive with the conventional diesel generator water pumping systems. The SPVWP system should be compatible with the local culture and practices to satisfy local wishes and needs, which also could be achieved by using local resources.

References

[1] World Health Organization and UNICEF. Water for life, WHO/UNICEF joint monitoring programme for water supply and sanitation, 2005. ISBN 92 4 156293 5.
[2] IEA Photovoltaic power system programme. International statistics. Annual report 2005, Implementing agreement on photovoltaic power system, 2005, online available at: 〈http://www.iea-pvps.org〉, hardcopy on file with author, retrieved on June 25, 2006.
[3] Energy Information Administration (EIA). Photovoltaic cell and module average prices, Renewable Energy Annual, 2004 Edition, online available at: 〈http://www.eia.doe.gov/cneaf/solar.renewables/page/rea_data/rea_sum.html〉, hardcopy on file with author, retrieved on July 01, 2006, 2000–2004.
[4] Holihan P. Technology, manufacturing and market trends in the US. and international photovoltaic industry, Energy Information Administration, Renewable Publications, online available at: 〈http://www.eia.doe.gov/cneaf/solar.renewables/rea_issues/solar.html〉, hardcopy on file with author, retrieved on July 10, 2006.
[5] Dunn PD. Appropriate technology: technology with a human face. New York: Schocken Books; 1979.
[6] Meah K, Fletcher S, Wan Y, Ula S. Solar photovoltaic water pumping to alleviate drought in remote locations, In: Proceeding of ASME power conference, May 2–4, Atlanta, GA, USA, 2006.
[7] Purohit P, Kandpal TC. Solar photovoltaic water pumping in India: a financial evaluation. Int J Ambient Energy 2005;26(3):135–46.
[8] Kaunmuang P, Kirtikara K, Songprakorb R, Heap S, Suwannakum T. Assessment of photovoltaic pumping systems in Thailand—one decade experience. Sol Energy Mater Sol Cells 2001;67(1–4):529–34.
[9] Espericueta ADC, Foster RE, Ross MP, Avilez OM, Rubio ARP. Ten-year reliability assessment of photovoltaic water pumping systems in Mexico. In: American solar energy society conference, Portland, OR, July 9–14, 2004.
[10] Roger JA. Water and photovoltaic in developing countries. Sol Cells 1982;6(3):295–308.
[11] Mustafizul AN, Rahman M. Cost-effective analysis on the suitability of photovoltaic pumping systems in Bangladesh. Sol Energy Mater Sol Cells 1993;30(2):177–88.
[12] Yahya HN, Sambo AS. Design and installation of solar photovoltaic powered water pumping system at Usmanu Danfodiyo University, Sokoto. Renew Energy 1995;6(3):311–2.
[13] Alajlan SA, Smiai MS. Performance and developing of PV—plant for water pumping and desalination for remote area in Saudi Arabia. Renew Energy 1996;8(1):441–6.
[14] Hamidat A, Benyoucef B, Hartani T. Small-scale irrigation with photovoltaic water pumping system in Sahara Regions. Renew Energy 2003;28(7):1081–96.
[15] Green MA, Emery K, King L, Igari S, Warta W. Solar cell efficiency tables (version 25). Prog Photovoltaics: Res Appl 2005;13(1):49–54.
[16] UNICEF. Press release, New York, March 22, 2005 [On-line], available at: 〈http://www.unicef.org/media/media_25643.html〉 hardcopy on file with author, retrieved on July 16, 2006.
[17] Roger JA. Theory of the direct coupling between DC motors and photovoltaic solar array. Sol Energy 1979;23(3):193–8.
[18] Clark R, Vick B. Performance comparison of tracking and non-tracking solar photovoltaic water pumping systems. In: Conference proceedings of the American society of agriculture engineers annual meeting, vol. 3, August 10–14, 1997.
[19] Bangladesh Bank, Central bank of Bangladesh, Exchange rate, as on July 16, 2006, online available at: 〈http://www.bangladesh-bank.org/〉.
[20] Brigham E, Gapenski L, Ehrhardt M. Financial management theory and practice, 9th ed. the Dryden Press, Harcourt Brace College Publisher; 1999.